

# Quiet time fluxes and radial gradients of low-energy protons in the inner and outer heliosphere

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Radial variations of low-energy ( $\sim 1$ -8 MeV) quiet-time fluxes of protons are examined at distances of 20-85 AU during low solar activity periods using Voyager 1-2 data and compared with Ulysses fluxes at 1-5 AU as well as IMP-8 and SOHO at Earth and Helios between 0.3 and 1 AU. To obtain nearly background-free fluxes, the data are based on a careful pulse-height analysis. Except for high solar activity periods, contaminated with solar particles, all fluxes are very low, of the order of, and below  $10^{-5}$  /(cm<sup>2</sup> s sr MeV). The Ulysses fluxes seem to be the lowest, whereas Helios and Voyager fluxes are nearly at the same level. The radial variation in 1-8 MeV suggests a negative gradient from 0.5 to about 2 AU that gradually turns positive beyond 2 AU. Whereas the true variation is difficult to infer between 5 and 17 AU due to solar contribution, from 30 to about 60 AU it exhibits a wide plateau, beyond which a slight increasing tendency is observed. At energies above  $\sim 6$  MeV a clear contribution of anomalous hydrogen is observed.

## 1. Introduction

Energetic particle fluxes in the heliosphere are subject to extremely large temporal variations amounting to 6-8 orders of magnitudes, diminishing towards both ends, near the energy of the solar wind plasma and of galactic cosmic rays. Although high-flux events are readily detected in the energy range in between, the nature and even the existence of a true lower background, which never disappears, has remained an open question. The determination of such a background is very difficult experimentally because the fluxes are very low and statistical errors are large. It is also problematic how to exclude minor solar and interplanetary events, solely on the basis of short-time increases in the time profile. The information about the true background could be the clue to understand the role of energetic particles in fundamental coronal processes.

Several aspects of such a background were studied by our group at energies of about 2-20 MeV at 1 AU [1, 2], and between 3 and 10 MeV at 0.3-1 AU [3]. A preliminary analysis of the Voyager 1 and 2 LECP data (not pulse height analyzed) indicated the presence of a plateau between 20 and 60 AU whereas the gradient changed sign from negative to positive beyond about of 60-70 AU [4, 5]. Here we concentrate on the radial variation by comparing the lowest fluxes obtained at Helios with those at Earth, Ulysses, and Voyager.

## 2. Observational results

The energetic particle data used in this study are from the Voyager Cosmic Ray Subsystem (CRS, PI: E.C. Stone, [6]), the Ulysses COSPIN Low Energy Telescope (LET, PI: R.B. McKibben, [7]), the Helios Cosmic Ray Experiment (PI: H. Kunow), the SOHO COSTEP instrument (PI: H. Kunow), and the IMP-8 EIS instru-

ment (PI: E.C. Stone). These all employed the  $dE/dx$  vs.  $E$  technique and identified protons in the energy range above about 2 MeV.

In order to obtain fluxes, which are free of contributions from transient increases as much as possible, intervals of very low and stationary fluxes have been selected on the basis of temporal profiles of counting rates. Since the geometry factors are small, one cannot expect perfect elimination of events. On the other hand, at high solar activity, fluxes sometimes do not reach a steady quiet level between large events, therefore it is difficult to infer the quiet-flux level at those periods. The next step is to get rid of the instrumental background. Unfortunately, 3-fold coincidences, which are really reliable for particle identification, are only available at higher (about  $>10$  MeV) energies, thus as we concentrate on the energy range of 1-10 MeV, only twofold coincidences could be used at best. Fortunately, at low rates, practically all protons are counted. To separate genuine fluxes from the instrumental background the procedure worked out in [1] for SOHO measurements and used to obtain proton fluxes at Helios [3] was adopted which allows estimating the instrumental background reliably.

Following this procedure 31 time intervals were selected for Voyager 1 between 1977 and 2002 (heliocentric radial distances: 1.04 to 84.5 AU), and 29 time intervals between 1977 and 2004 for Voyager 2 (1.25 to 75 AU). Then the energy range of 1.8 to 8.1 MeV was split into 5 logarithmically equal intervals, for which the proton background was separated from genuine fluxes. The same procedure has been applied for Ulysses during the solar minimum period of 1994 to 1997 and yielded 12 time intervals with a total time of 301 days (radial distances 1.4-4.8 AU). Here the energy ranges chosen coincided with those of the CRS instruments at both Voyagers. The fluxes of protons have been determined in these intervals by using the effective measuring time. The Ulysses fluxes were then binned in 0.5 AU intervals and then averaged using weights according to the length of time intervals.

### 3. Variation with radial distance

The radial variation at both Voyager 1 and 2 in 5 energy channels, depicted in Figure 1, suggests a gradual decrease outwards up to about 20 AU. However, all fluxes are clearly dominated by solar particles in the first intervals during high solar activity in 1979-1984 (V1: until 20 AU, V2: until 16 AU), therefore these cannot be directly compared to the quiet fluxes. As V2 arrived at 17 AU in 1985, near solar minimum, the

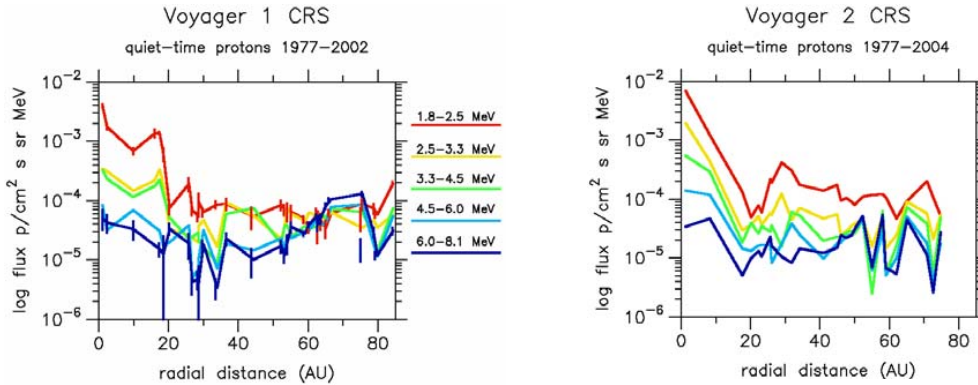


Figure 1. Variation of proton fluxes during quiet periods aboard Voyager 1 (left panel, vertical bars: statistical errors) and 2 (right panel) between 1977 and 2004 in 5 different energy ranges.

fluxes between 17 and 21 AU are considerably lower, then increase again due to the increased contribution of solar particles. In the distance range of about 30 to 60 AU a wide plateau is observed in the radial profiles at both Voyagers, with very low fluxes at all energies. Both plots match relatively well indicating little difference between the northern (V1) and southern (V2) hemispheres.

Figure 2 displays fluxes obtained for Ulysses LET while the s/c moved inward then outward during the 1994-97 solar minimum period. The fluxes are extremely low, by a factor of about 3 smaller than those at Voyagers (see Fig. 2). This in principle could be due to a lower instrumental background, which would mean unaccounted contamination at all the rest of measurements; however, it is more probably a genuine effect, possibly due to the high mean heliographic latitude of Ulysses. Figure 3 compares the above with earlier findings of [1] and [3]. Helios data are only available above  $\sim 4$  MeV, on IMP-8 we included the EIS fluxes obtained in 1986. The two SOHO data points were taken from [1].

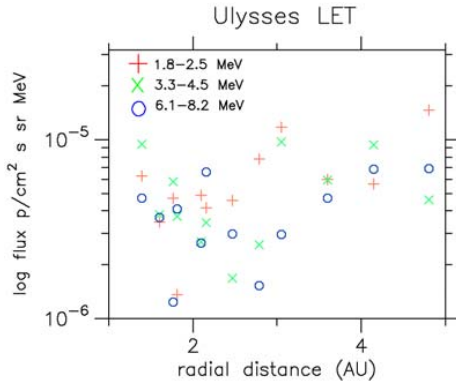


Figure 2. Variation of Ulysses proton fluxes in 3 energy intervals in 12 quiet intervals.

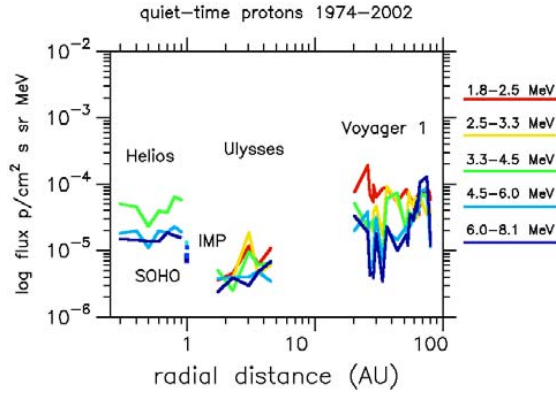


Figure 3. Comparison of Helios, IMP, SOHO with Ulysses and Voyager 1 in 5 energy ranges.

The Ulysses fluxes are by a factor of  $\sim 4$  lower than Helios (1975-76), and Voyager fluxes are nearly at the same level. At  $< 20$  AU high Voyager fluxes are due to solar activity, the comparison of V1 and V2 indicates very little difference between northern and southern latitudes. The radial variation in five energy intervals suggests a negative gradient from 0.5 to about 2 AU, supported by IMP-8 (1986) and SOHO (1996) fluxes that are significantly lower but still higher than Ulysses intensities of the same energies. The gradient is positive for the Ulysses points between 2 and 5 AU. Whereas the true variation is difficult to infer between 5 and 17 AU due to solar contribution, the gradient seems to be roughly constant. Its numerical value is about  $2 \text{ to } 4 \times 10^{-6} / (\text{cm}^2 \text{ s sr MeV}) / \text{AU}$  for 1.8-2.5 MeV protons, and  $\sim 10^{-6} / (\text{cm}^2 \text{ s sr MeV}) / \text{AU}$  for  $\sim 6$ -8.1 MeV. From 30 to about 60 AU, however, a wide plateau is observed at both Voyagers. At  $\sim 2$  MeV, the slope is slightly negative, similar to the radial profiles of 0.5-2 MeV LECF proton fluxes [5], and has a small positive value at  $\sim 7$  MeV. Beyond about 60 AU a slight increasing tendency is seen at V1, which is less clear at V2. At energies above  $\sim 6$  MeV it is probably mostly due to the contribution of anomalous hydrogen, having a highest flux in 1999 at both Voyagers [8].

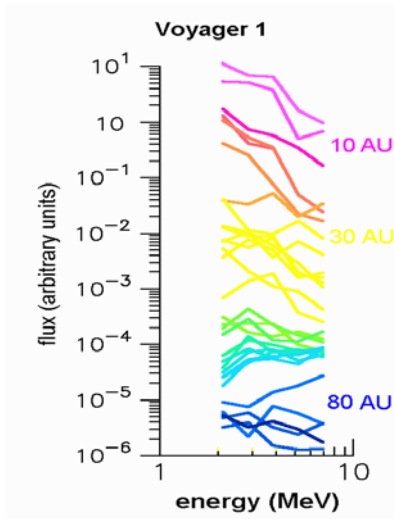


Figure 4. The proton energy spectra between 1.8 and 8.1 MeV at V1 at distances 10 to 85 AU (color coded and vertically shifted according to radial distance).

The energy spectra of quiet-time protons as shown in Figure 4 are subject to drastic changes along the Voyager 1 orbit. Dominant solar contribution closer to the Sun, as told above, is responsible for typical falling spectra with exponents of 2-3. Near 30 AU the spectra are quite variable, then at 65-70 AU the contribution of anomalous protons result in flat and even increasing spectra (in 1996-98). Falling spectra are restored beyond 75 AU.

The radial variation of quiet-time low-flux protons over distances from 0.3 to 85 AU suggests that the low-flux population below 10 MeV is composed of perhaps three different populations. Tentatively, high Helios fluxes can be explained in terms of a steady solar source, perhaps nano-, or picoflares, but adiabatic deceleration and the variation of the diffusion mean free path with radial distance probably also plays an important role. The long plateau can be due to acceleration at corotating interaction regions, and the small positive gradient beyond 60 AU to the proximity of the termination shock, i.e., to the contribution of anomalous particles during low solar activity or may result from acceleration due to increased wave activity.

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